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INTRODUCTION

A series of new candidate materials for use as an improved restraint layer in the shuttle space suit were woven by N. F. Doweave, Inc. under contract to the National Aeronautics and Space Administration (NAS 9-14777). This effort produced three promising candidate materials for use as an improved restraint layer for the shuttle space suit.

It has been substantiated by test and evaluation that the objectives of this fabric development effort have been achieved. N. F. Doweave has demonstrated the feasibility of weaving triaxial fabrics in tight, low porosity configurations with yarns of appropriate sizes and materials. N. F. Doweave has confirmed by test and analysis the stability and isotropy of triaxial fabrics. N. F. Doweave has provided a sound empirical and analytic base for carrying forward subsequent programs involving triaxial fabrics.

Two of the new triaxial fabric constructions developed under this contract, namely, BP44P and BP40M can be reproduced on a production basis. Both new fabric constructions afford excellent strength-to-weight ratio and exhibit much improved tear strength and shear resistance over commercially available biaxial fabrics.

The other new triaxial fabric construction (BP40K) is made from 100% aramid yarns. This fabric construction affords a still greater improvement in physical properties over BP44P and BP40M, but requires further development to maximize cost performance.

TRIAxIAL FABRIC DESIGN CRITERIA

In the performance of the present investigations, NASA and N. F. Doweave, with a view toward the simplification of fabric design elected to study and develop the Bi-Plain weave pattern for pressure suit applications.

In the Bi-Plain weave construction, less porosity is achieved by weaving the horizontal or fill yarns over and under the two sets of bias or warp yarns. Otherwise, both bias yarns are in the same position as in the basic weave. The Bi-Plain weave may be considered one of the triaxial counterparts of the traditional plain weave, in which the fill yarn is woven over and under each warp yarn, one by one. Using the Bi-Plain construction with the proper selection of yarns, we now have the ability to derive a closed structural fabric in the plain view - with exceptional dimensional stability.

N. F. Doweave exerted its best efforts to weave three candidate materials. Each candidate material was fabricated on full scale production equipment, therefore, a minimum quantity of material was required to fabricate each sample. The fabric samples were identified as follows; BP44P is a Bi-Plain triaxial fabric composed of 440 denier Dacron yarns; BP40M is a Bi-Plain triaxial fabric composed of 400 denier Ncmex yarn; and BP40K is a Bi-Plain triaxial fabric composed of 400 denier Kevlar 29 yarns.

The description of the candidate triaxial fabric constructions is given in Table 1.

Table 1. Description of Filament Triaxial Fabric Samples

	<u>BP44P</u>	<u>BP40M</u>	<u>BP40K</u>
Yarn Type	Dacron	Nomex	Kevlar 29
Yarn Construction			
Warp	220/2-4Z, 2S	200/2-4Z, 2S	200/2-10Z, 5S
Fill	220/2-4Z, 2S	200/2-4Z, 2S	200/2-20Z, 10S
Ends Per Inch	40 x 40	38 x 38	40 x 40
Picks Per Inch	40	38	41
Yarns Per Square Inch	120	114	121
Aeral Density (oz/yd ²)	7.5	6.6	6.9
Weave	Bi-Plain	Bi-Plain	Bi-Plain
Width (in)	72	75	75.5

N. F. Doweave's efforts in fabric finishing were consolidated with the E. I. DuPont de Nemours & Co., Inc. and O. B. Dyers. Foremost in this effort was the determination of optimum finishing procedures for treating triaxial fabric. The unique construction of triaxial fabric required modification to existing scouring techniques in order to maintain the desired yarn intersections. Heat setting techniques were also modified to provide for the reaction of yarns running diagonally across the tenter frame as well as the normal filling and machine directions.

Under the original requirements of contract NAS 9-14777 N. F. Doweave supplied 50 yard lots of BP44P, BP40M and BP40K. The fabric supplied to NASA was utilized in joint cycle testing study programs.

Based on the results of the initial effort, NASA amended contract NAS 9-14777 to include a minimum of 100 linear yards of triaxial fabric representing the most promising construction. After careful review of the three candidate triaxial constructions it was decided jointly by NASA and N. F. Doweave that the optimum construction for further development was BP44P. At this time, a hybrid construction was considered. This construction would be constructed from polyester warp yarns and aramid filling yarn. In order to fabricate the desired fabrics, N. F. Doweave modified the weave texture and finishing requirements in order to meet the minimum weight requirement of 7.0 oz/yd².

The candidate fabrics supplied under this portion of the contract were identified as follows; BP44P-35 is a Bi-Plain triaxial fabric composed of 440 denier Dacron yarns; SP44PK-48 is a Sail-Plain triaxial fabric composed of 440 denier Dacron warps and 200 denier Kevlar 29 filling.

The description of these triaxial fabric constructions is given in Table 2.

Table 2. Description of Optimum Fabric Constructions

	<u>BP44P-35</u>	<u>SP44PK-48</u>
Yarn Type	Dacron	Dacron Warp/Kevlar 29 Fill
Yarn Construction		
Warp	220/2-4Z, 2S	220/2-4Z, 2S
Fill	220/2-4Z, 2S	200/1-5Z
Ends Per Inch	38 x 38	37 x 37
Picks Per Inch	35	48
Yarns Per Square Inch	111	122
Aeral Density (oz/yd ²)	6.8	6.0
Weave	Bi-Plain	Sail-Plain
Width (in)	74.75	76.75

FIBER/YARN DESIGN CRITERIA

Due to the revolutionary nature of the triaxial configuration and the limited capability of those machines available, only plied yarn constructions were considered. Although considerable yarn data was available for both Dacron and Nomex yarn, little was known about Kevlar 29 yarn. Therefore, during the first few months of this program, N. F. Doweave evaluated various yarn designs using Kevlar 29 fiber to determine how to handle Kevlar 29 through twisting, winding, warping, and weaving so as to obtain the highest possible yarn to fabric strength translation efficiency.

N. F. Doweave's efforts in yarn development were consolidated with the Philadelphia College of Textiles and Science, Philadelphia, Pa. Foremost in this effort was the determination of optimum yarn preparation procedures for Kevlar 29 to insure weavability on triaxial weaving machinery.

A small amount of Kevlar 29 yarn was procured and forwarded to the Philadelphia College of Textiles and Science for the purposes of defining the yarn construction for weaving. Table 3 identifies the yarn constructions that were made and Table 4 summarizes the test results.

Table 3. Experimental Yarn Constructions

200 denier Kevlar 29, 0 TPI
200 denier Kevlar 29, 0 TPI, 2 plied with 3.5 S TPI
200 denier Kevlar 29, 3Z TPI, 2 plied with 3.5 S TPI
200 denier Kevlar 29, 5Z TPI, 2 plied with 2.5 S TPI
200 denier Kevlar 29, 10Z TPI, 2 plied with 5 S TPI
200 denier Kevlar 29, 18Z TPI, 2 plied with 9 S TPI

Table 4. Comparison of Experimental Yarn Constructions

<u>Construction</u>	<u>Breaking Strength (Kgs)</u>		<u>Elongation (%)</u>	
	<u>Mean</u>	<u>SD*</u>	<u>Mean</u>	<u>SD*</u>
0 TPI	3.40	.12	2.76	0.0
0 TPI,				
2 plied with 3.5S TPI	9.34	.28	3.15	.28
2Z TPI,				
2 plied with 3.5S TPI	8.87	.24	2.92	.21
5Z TPI,				
2 plied with 2.5S TPI	8.92	.34	2.92	.21
10Z TPI,				
2 plied with 5S TPI	8.95	.45	3.15	0.0
18Z TPI,				
2 plied with 9S TPI	8.92	.295	3.94	.28

* SD means Standard Deviation

For the first experimental yarn run, all yarn sample constructions were down twisted at a spindle speed of 4000 rpm. No processing aids were applied to the yarn. It was observed, utilizing a microscope, that minimum filament damage occurred due to the high twist levels. It was also determined that the standard deviations were lower than normally expected for similar yarn constructions.

Careful review of this test data indicated that a Kevlar 29 yarn prepared with a high degree of singles twist and plied to balance twist afforded excellent strength to elongation ratios. As a result, a second experimental lot of yarn was twisted with 18 turns of Z twist in a singles yarn and plied with 9 turns of S twist in the plied construction. This yarn experiment reconfirmed the original test results and insured repeatability of the yarn preparation process. A comparison of the two lots of yarn are compared in Table 5.

Table 5. Comparison of Lot 1 and Lot 2 Yarn Constructions
made with 18Z TPI, plied with 9 S TPI

<u>Breaking Strength (Kgs)</u>				<u>Elongation (%)</u>			
<u>Mean</u>		<u>SD</u>		<u>Mean</u>		<u>SD</u>	
<u>Lot 1</u>	<u>Lot 2</u>	<u>Lot 1</u>	<u>Lot 2</u>	<u>Lot 1</u>	<u>Lot 2</u>	<u>Lot 1</u>	<u>Lot 2</u>
8.92	8.67	.295	.21	3.94	4.77	.28	.09

Yarn samples of the second experimental lot were also down twisted at a spindle speed of 4000 rpm. Water was used as a processing aid. Although the second sample showed a 7% decrease in mean breaking strength, the resultant elongation increased by 21%. In addition, a much lower standard deviation was experienced.

As a result, the throwster (Atwater Throwing Company, Plymouth, Pa.) was directed to put 18 turns of Z twist in a singles yarn and then two ply the singles with 9 turns of S twist in the plied construction.

PROBLEMS ENCOUNTERED

N. F. Doweave experienced considerable yarn preparation difficulties, primarily in the scheduling of the yarn to be thrown. The Atwater Throwing Company refused to schedule the required poundage to be thrown. This schedule uncertainty was caused by the required reduction in spindle speed and the criticality of processing Kevlar 29 yarn on throwing equipment.

To continue the program effort, N. F. Doweave negotiated an arrangement with the E. I. DuPont Company in Wilmington, Delaware for the purposes of yarn preparation. Due to the proposed advancement of the state of the art in throwing Kevlar 29, DuPont would not throw the yarn with 18 turns of twist in the singles and 9 turns of twist in the plied construction. They would only consider throwing 10 turns of twist in the singles and 5 turns of twist in the plied construction. Although this was not deemed the ideal construction at the time of yarn definition, N. F. Doweave, in light of the scheduling difficulties at Atwater Throwing Company elected to change the yarn requirements in order that the E. I. DuPont Company could throw the yarn.

It should be noted, that the yarn design change only affected the warp system. Filling yarn remained as originally designed. Since the Atwater Throwing Company would not be twisting and plying the proposed Kevlar yarn construction, N. F. Doweave negotiated an arrangement with the Philadelphia College of Textiles and Science and the Hemingway and Bartlet Corporation, for the purposes of yarn preparation for the filling yarn system. The Philadelphia College of Textiles and Science made a yarn with 20 turns of twist in the singles and 10 turns of twist in the plied construction. The Hemingway and Bartlet Corporation made a yarn constructed with 17 turns of twist in the singles and 13 turns of twist in the plied construction. Additionally, the Hemingway and Bartlet yarn construction would also be lubricated with silicone.

In the interest of optimizing fabric performance, N. F. Doweave wove approximately 5 yards of fabric with three different filling yarn constructions identified as follows:

5 yards of fabric using the yarn prepared by the Philadelphia College of Textiles and Science constructed with 20 turns of twist in the singles yarn and 10 turns of twist in the plied yarn;

5 yards of fabric using the yarn prepared by the Hemingway and Bartlet Corporation constructed with 17 turns of twist in the singles yarn and 13 turns of twist in the plied yarn;

5 yards of fabric using a yarn prepared by the E. I. DuPont Company constructed with 10 turns of twist in the singles yarn and 5 turns of twist in the plied yarn (same yarn design as the warp construction).

Fabric specimens of each construction were thoroughly evaluated at Philadelphia College of Textiles and Science for the purposes of evaluating the effect of twist on elongation. Samples of each construction were forwarded to NASA for review and investigation. Test results indicated that the yarn prepared with 20 turns of Z twist in the singles and 10 turns of S twist in the plied construction had 29.9 per cent greater elongation than a yarn produced with 10 turns of Z twist in the singles and 5 turns of S twist in the plied construction and had 22 percent greater elongation than a yarn prepared with 17 turns of S twist in the singles and 13 turns of Z twist in the plied construction. The results of this test are summarized in Table 6.

Table 6. Comparison of Experimental Filling Yarns

<u>Yarn Construction</u>	<u>Percent Elongation</u>	<u>Standard Deviation</u>
10Z - 5S	5.42	.165
17S - 13Z	5.77	.689
20Z - 10S	7.04	.625

Since fabric elongation directly correlates to flex life, a test was designed to evaluate each filling yarn construction under a state of dynamic stress.

The "hour glass" flex test method designed by ILC Dover, Frederica, Delaware was used. The specimen in this test is a cylinder shaped like an hour glass. The smallest diameter is indexed at the center of the specimen. This shape is developed from flat patterns and the hour glass shape causes the specimen to flex at the smallest diameter. The test specimen is pressurized to 4.0 psi for the duration of the test. Test specimens, which are not coated with a gas retentive layer, require a high modulus bladder to retain the gas while the specimen serves as a restraint. The specimen is then attached to the flex machine. This machine is driven by an AC variable speed motor coupled by a V-belt to a gear box. From the gear box, an arm is attached to a shaft which drives the specimen holder and counter. The cycle rate may be varied by changing the speed of the AC motor. A cycle is defined as starting at zero, moving 45° left, back through 0°, 45° right, and back to zero. Test results are summarized in Table 7. It can be concluded from the results of this test that a yarn prepared with a high degree of singles twist and then plied to balance the yarn twist affords maximum flex life translation into woven fabric construction.

Table 7. Comparison of Fabric Constructions After "Hour Glass"
Flex Testing of Filling Yarn System

<u>Yarn Construction</u>	<u>No. of Cycles</u>
10Z - 5S	130,306
17S - 13Z	182,707
20Z - 10S	400,300

Therefore, the Kevlar 29 sample woven under contract (NAS 9-14777) had a warp yarn system designed with 10 turns of Z twist in the singles and 5 turns of S twist in the plied construction while the filling yarn system was designed with 20 turns of Z twist in the singles and 10 turns of S twist in the plied construction.

PROBLEMS ENCOUNTERED WEAVING THE KEVLAR 29 FABRIC CONSTRUCTION

During initial weaving attempts it was observed that a combination of shedding geometry and weaving cycle, acting through a low elongation yarn, resulted in a predictable slack shed influencing yarn passage. As a result, slack yarns were being cut out due to bad passage into the made shed as well as the unmade shed.

In order to reduce the sensitivity to slack yarn, the shedding sequence was altered. This change required significant modification to the heddle transfer driving mechanism since the transfer sequence also changed with shedding sequence. This change essentially eliminated the problem of cutting out warp yarn during passage into the made shed. The remaining problem was bad passage of yarns into the unmade shed position. The shedding sequence does not alter the unmade shed geometry or the relationship between heddles and yarn in this position of the cycle.

We continued to experience random slack yarns in the unmade shed which resulted in bad passage and cut out warp ends. The frequency of bad warp passage remained at an excessive level consistent with good quality fabric.

We then experimented with drop wires to accumulate random slack away from the weaving element. This technique seemed to improve the weavability temporarily, but the frequency of bad warp passage still persisted and the drop wire experiment was discontinued.

We then elected to experiment with beam tension to eliminate slack yarns. Previous to this experiment we were putting an excess amount of tension on the beams in an attempt to pull out and tighten slack yarns. By reducing the warp beam tension, we were effectively making the entire warp slack in the unmade shed. We then attached to the weaving machine an air blower system which effectively blew away from the weaving element the slack yarns in the unmade shed. This alternative, along with a much slower machine speed, reduced the high frequency of bad warp passage. We continued to weave BP40K by this weaving alternative until the order was completed.

FUTURE CONSIDERATIONS

Based on our experience to date N. F. Doweave considers both BP44P and BP40M production products. N. F. Doweave does not consider BP40K a production product at this time. Before substantial progress can be made or before production quantities of this fabric can be procured, the following machinery modifications are considered essential:

1. Shedding Sequence - The Bi-Plain shedding sequence should be changed to one where heddles shed between heddles in the same plane (alpha to alpha prime and beta to beta prime). This change was simulated for the weaving evaluation and contributed significantly to solution of the warp passage problems. Machines currently available were not constructed specifically for this technique and machine speed was therefore restricted in this trial.
2. Tabbed Heddles - Using the above shedding sequence, we were able to avoid most of the passage problems into the made shed. With existing heddles (no tabs), we experienced excessive warp breaks resulting from bad passage in the unmade shed position. Tabbed heddles, which would maintain the alignment of heddles, and therefore yarn, in the unmade shed, should significantly reduce this problem.
3. Beater System - Any future weaving trials of the BP40K should be done on a machine where the beater system has been modified to withstand the "beat back" loads experienced. Three beater arms were broken during the weaving of the sample yardage.
4. Additionally, design work is required for an improved length compensation system, take up system and filling cutters in order to produce first quality fabric.

It is estimated that a substantial amount of money would be required to make the necessary machinery modifications described above.

The results of the evaluation show that, unless Kevlar can be processed through the triaxial weaving machine without substantial damage, the Dacron and Nomex fabric constructions offer the best choice. Perhaps Kevlar yarns can be sized and lubricated for improved manipulation through the triaxial machine. However, in addition to proper yarn sizing, Kevlar filaments must avoid critical compressive loading which is accentuated at any small radius of curvature or point of concentrated pressure.

The new material advancement explored during this effort represents the beginning of a new class of restraint material. It is hoped that subsequent programs will be able to build upon this base work by providing a suitable growth environment for the new triaxial technology.